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# A Bilevel Transactive Energy Framework for Peer-to-Peer Solar Trading, EV Charging Flexibility, and Distribution-Network Congestion Management

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## Abstract

Peer-to-peer solar trading can empower prosumers but poses congestion risks for distribution networks. A bilevel framework that separates market functions from network oversight can enable secure, efficient transactive energy. This article proposes a conceptual bilevel transactive energy framework that coordinates P2P solar trading, EV charging flexibility, and active congestion management. The framework is intended as an architectural contribution rather than a mathematical optimization model. The framework is designed conceptually, with an upper market layer and a lower network operation layer. Information flows, decision logics, and validation pathways are described without mathematical formulation. The framework defines clear roles for market participants and the DSO, integrates EV flexibility as a congestion-mitigation resource, and includes a feedback mechanism from network to market. Five tables summarize the architecture, component functions, and validation plan. The proposed conceptual architecture can guide future software implementations, regulatory sandbox designs, and field pilots. It bridges the gap between market innovation and grid reliability.

**Keywords** Congestion management, Transactive energy, Bilevel framework, Peer-to-peer solar trading, EV flexibility, Conceptual architecture

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## Introduction

Peer-to-peer solar trading would allow households, commercial prosumers, and community microgrids to exchange locally generated electricity through decentralized or semi-decentralized market arrangements. Early P2P trading studies show that local energy exchange can improve prosumer participation and create new value streams for distributed solar resources [1]. At the same time, community-level energy trading must be coordinated carefully because individual transactions can influence feeder loading, voltage behavior, and operational security [2]. This article therefore frames P2P trading not only as a market design problem but also as a distribution-network coordination problem.

The main tension arises because a market-cleared trade may be economically attractive while still being physically difficult for the grid to accommodate. Game-theoretic and auction-based P2P mechanisms have demonstrated how prosumers can negotiate prices and quantities [3], while comparative auction studies show that market rules strongly influence participant behavior [4]. However, these market mechanisms require an architectural interface with network operation so that trading outcomes remain compatible with distribution constraints. A bilevel conceptual framework would

help separate commercial coordination from technical feasibility checking without merging all decisions into a single opaque process.

The proposed framework is inspired by bilevel and transactive energy studies in which a higher coordination layer interacts with a lower operational layer. Fernandez *et al.* [2] show how community energy management can be structured through bilevel coordination, while Singh *et al.* [5] extend this logic toward stochastic P2P market design. More recent work on renewable microgrids connected to distribution networks also motivates the need for market-network coordination [6]. Building on these ideas, this article proposes a prose-based architecture for coordinating solar trades, EV flexibility bids, and congestion feedback.

The contribution of this conceptual article is to describe the components, roles, information exchanges, and decision-making sequence of a bilevel transactive energy framework. Unlike studies that present formal scheduling models or numerical simulations, the present article deliberately avoids equations, algorithms in mathematical notation, and quantitative results. It focuses on how an upper-level market layer would exchange candidate trading schedules with a lower-level network layer, following the broader direction of network-aware P2P scheduling [7]. The result is an architectural framework that could support future implementation, simulation, and field validation.

## P2P Trading Problem

### The promise and risks of peer-to-peer trading

P2P trading promises to transform passive consumers into active market participants by allowing prosumers to sell local solar surplus directly to neighbors. In a community microgrid, this kind of exchange can improve local utilization of renewable generation and strengthen participant engagement [1]. Game-theoretic studies also indicate that prosumer incentives can be aligned through carefully designed local trading rules [3]. Yet these same trades may create operational risks when many prosumers export or import simultaneously without awareness of feeder-level constraints.

### The congestion blind spot

The congestion blind spot appears when market participants focus on bilateral economic preferences while overlooking the shared physical limits of the distribution grid. Tarashandeh and Karimi [8] emphasize that P2P energy trading must preserve the independent nature of agents while still respecting distribution-network constraints. Personalized P2P trading designs also show that user preferences and AC network constraints can interact in complex ways [9]. Therefore, a conceptual framework must make network feasibility visible to the market without eliminating participant autonomy.

### The need for a bilevel approach

A bilevel approach would be structured as two interacting layers, with the upper level responsible for market coordination and the lower level responsible for network oversight. This separation is consistent with bilevel stochastic market design [5] and with renewable microgrid studies that place P2P trading within distribution-grid operating conditions [6]. The upper layer would match solar offers, demand bids, and EV flexibility bids, while the lower layer would review the resulting schedule for congestion risk. If the lower layer identifies a technical concern, it would send feedback to the market so that the trade pattern could be adjusted conceptually before implementation.

## System/Market Description

### Actors and their assets

The proposed system would include solar prosumers, conventional consumers, EV owners, aggregators, community market operators, and the distribution system operator. Prosumers would provide solar surplus offers, consumers would

submit demand preferences, and EV owners would contribute flexible charging or discharging availability where technically and contractually appropriate. Frameworks for prosumer participation in P2P trading and flexibility markets show that these roles can coexist in a layered market setting [10]. The DSO would not act as a commercial counterparty but would remain responsible for maintaining secure feeder operation.

### The physical distribution network

The physical network would be represented conceptually as a low- or medium-voltage distribution grid with feeders, transformers, connection points, solar installations, EV chargers, and controllable demand resources. Distribution-aware P2P studies indicate that local trades can influence voltage profiles and line loading, especially when solar exports are concentrated in specific areas [7]. Network congestion management research further suggests that time sequencing matters because trades accepted in one interval can affect the feasibility of later intervals [11]. In this framework, the grid layer is responsible for translating physical limits into feedback that the market can understand.

### P2P market structure

The P2P market would be structured as a coordination environment in which participants submit offers, bids, preferences, and flexibility options. Decentralized energy trading frameworks for retailers and prosumers show that market design can accommodate different degrees of central coordination [12]. Shared storage studies also demonstrate that market structures may include intermediary community resources that support balancing among households [13]. In the proposed framework, the market is not defined by a single pricing formula but by its functional responsibility to match local supply, demand, and flexibility while remaining responsive to network feedback.

### EV charging infrastructure and flexibility potential

EV charging infrastructure would be treated as both a source of additional demand and a flexible asset that can help reshape local load patterns. Transactive EV charging studies show that charging schedules can be coordinated through market-based signals [14]. Reserve-management work further illustrates that EV aggregators can represent flexible charging resources in structured decision processes [15]. In the proposed architecture, EV flexibility would enter the upper-level market as a bid or service offer and would be reviewed by the lower-level network layer for its ability to support congestion relief.

### Information and communication assumptions

The framework assumes that participants and aggregators can exchange standardized information with the market layer, including availability, preferences, asset status, and accepted transactions. Fully decentralized energy sharing studies for smart buildings and aggregated EVs show that local battery systems and EV fleets can exchange operational information without requiring complete central control [16]. The framework also assumes that the DSO can communicate operating envelopes, congestion warnings, or revised network limits to the market layer. These assumptions are summarized in Table 1, which identifies the main components, participants, assets, and conceptual operating conditions.

**Table 1.** Roles, assets, information exchange, and operational assumptions of participants in the peer-to-peer local energy trading framework

| Component or participant | Primary role in the framework                                 | Physical or digital asset involved           | Key information exchanged                                                  | Conceptual assumption                                                               |
|--------------------------|---------------------------------------------------------------|----------------------------------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Solar prosumer           | Offers local solar surplus and may buy from peers when needed | Rooftop PV, smart meter, home energy gateway | Solar availability, export offer, demand preference, accepted trade status | Prosumers can express trading preferences while remaining subject to network limits |

|                                     |                                                                       |                                                               |                                                                               |                                                                          |
|-------------------------------------|-----------------------------------------------------------------------|---------------------------------------------------------------|-------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Conventional consumer               | Purchases local energy through the P2P market                         | Smart meter, controllable load where available                | Demand bid, preferred supply source, willingness to shift consumption         | Consumers may participate without owning generation assets               |
| EV owner                            | Provides flexible charging demand and possible discharge availability | EV battery, charger, mobility schedule                        | Charging need, plug-in window, flexibility bid, minimum mobility requirement  | EV flexibility is voluntary and bounded by user mobility needs           |
| EV aggregator                       | Aggregates distributed EV flexibility for market participation        | Aggregation platform, charging network interface              | Aggregated flexibility offer, charger status, dispatch confirmation           | Aggregation simplifies market interaction for many small EV resources    |
| Community market operator           | Coordinates P2P matching and settlement preparation                   | Digital market platform                                       | Offers, bids, flexibility services, candidate trade schedule                  | Market operation is distinct from network security assessment            |
| Distribution system operator        | Monitors network feasibility and communicates constraints             | Feeder monitoring system, network model, operational platform | Congestion warning, operating envelope, technical feedback                    | The DSO safeguards the grid without directly selecting commercial trades |
| Shared storage or nanogrid resource | Supports balancing, flexibility, and local service provision          | Battery storage, nanogrid controller                          | State availability, charge or discharge service offer, local balancing signal | Community resources can complement bilateral trades                      |
| Communication infrastructure        | Enables market-network coordination                                   | Metering, secure data exchange, platform interfaces           | Participant data, market outcomes, network feedback, settlement records       | Timely and interoperable communication is necessary for coordination     |

## Upper-Level Market Architecture

### Market clearing function

The upper-level market layer would be responsible for collecting participant offers, demand bids, and flexibility bids before forming a candidate set of local transactions. Bilevel community energy management research positions the upper layer as the coordination point where trading preferences are organized before network feasibility is evaluated [2]. The market layer would not guarantee physical deliverability by itself; rather, it would prepare a proposed trading schedule for subsequent review. In this sense, market clearing is treated as an architectural function rather than as a mathematical procedure.

### Matching solar surplus and demand

Solar surplus matching would connect prosumers with buyers whose demand can be served locally under the rules of the community market. Auction-based P2P studies show that bidding strategies and market mechanisms can influence which buyers and sellers are matched [4]. The framework would therefore allow the market layer to consider price preference, local origin preference, and timing preference when forming candidate matches. These candidate matches would remain provisional until the lower-level network layer verifies that the associated power flows are acceptable.

## EV flexibility bid integration

EV flexibility bids would be integrated into the market as adjustable charging demand, deferred charging, charging acceleration, or potentially discharge support where permitted. Network-aware coordination of aggregated EVs shows that charge-discharge flexibility can be represented as a resource for distribution operation [17]. The market layer would receive EV flexibility offers from individual owners or aggregators and align them with periods when solar surplus or congestion relief value is expected. The key architectural role of the market is to make EV flexibility visible alongside energy offers rather than treating EV demand as fixed.

## Price signals and settlement

Price signals would communicate the relative value of solar energy, demand response, and flexibility services within the P2P market. Transactive pricing research shows that Stackelberg-style coordination can be used to align demand response with distribution-system objectives [18]. In the proposed framework, prices would be conceptual coordination signals that guide participant behavior and support settlement after network approval. Settlement records would reflect accepted trades, adjusted flexibility commitments, and any market revisions triggered by network feedback.

## Outputs to the lower level

The upper-level market would send candidate schedules, expected injections, expected withdrawals, EV charging adjustments, and flexibility commitments to the lower-level network layer. Multi-market nanogrid studies demonstrate that energy and ancillary service exchanges can be coordinated through structured information flows [19]. Ancillary service bidding research also shows that P2P communities can provide services beyond simple energy exchange when their commitments are clearly communicated [20]. **Table 2** summarizes the upper-level market functions, the information they receive, the outputs they produce, and the conceptual decision logic they apply.

**Table 2.** Upper-level market functions, inputs, outputs, decision logic, and interface with the network (lower-level) layer in the peer-to-peer energy trading framework

| Upper-level function        | Main inputs                                                      | Main outputs                                  | Decision logic in conceptual terms                                      | Interface with lower level                                     |
|-----------------------------|------------------------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------|
| Participant registration    | Asset type, location, metering status, market eligibility        | Verified participant profile                  | Confirms who can trade and what resources they can represent            | Sends participant-location mapping for network association     |
| Offer and bid collection    | Solar offers, demand bids, EV flexibility bids, user preferences | Structured market order set                   | Organizes commercial intentions before matching                         | Provides expected injection and withdrawal ranges              |
| Solar-demand matching       | Available solar surplus, buyer demand, timing preference         | Candidate P2P trade schedule                  | Prioritizes feasible commercial matches subject to later network review | Sends provisional trade pattern to network layer               |
| EV flexibility coordination | Charging windows, flexibility offers, aggregator bids            | Candidate flexibility commitments             | Aligns flexible charging with solar availability and congestion needs   | Sends expected charging adjustments by location and interval   |
| Price signaling             | Market preferences, local scarcity, flexibility value            | Indicative market prices and settlement basis | Communicates incentives without overriding network security             | Receives constraint feedback that may influence revised prices |

|                         |                                                                        |                                               |                                                                 |                                                          |
|-------------------------|------------------------------------------------------------------------|-----------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------|
| Settlement preparation  | Accepted trades, revised schedules, flexibility delivery confirmations | Settlement records and participant statements | Records obligations after market-network consistency is reached | Uses network-approved schedules as settlement reference  |
| Feedback interpretation | Congestion warning, operating envelope, network constraint message     | Revised market request or trade adjustment    | Converts technical feedback into market-facing revision needs   | Returns adjusted candidate schedule for further checking |

## Lower-Level Network Architecture

### Network state monitoring

The lower-level network layer would be responsible for observing the operational condition of the distribution grid after receiving candidate market outcomes. Distribution-network studies on P2P trading and scheduling emphasize that technical feasibility depends on the location and timing of prosumer injections and withdrawals [7]. The monitoring function would consider feeder loading, voltage behavior, transformer stress, and the spatial distribution of EV charging demand. Its purpose is to determine whether the candidate market schedule appears compatible with secure operation.

### Congestion detection and assessment

Congestion detection would identify whether the candidate set of P2P trades and EV schedules could create thermal overload, voltage deviation, or local bottlenecks. Research on P2P trading under distribution constraints shows that congestion assessment must preserve agent independence while still identifying technically problematic transactions [8]. Voltage-regulation service studies further suggest that prosumers may contribute corrective services when network conditions require support [21]. In the proposed framework, congestion assessment would not rank participants mathematically but would classify the candidate schedule as acceptable, conditionally acceptable, or requiring revision.

### Feedback signals to the market

When the network layer detects a potential violation, it would send feedback to the upper-level market in a form that can be used for trade revision. Fairness-regularized DLMP-based transactive mechanisms show that network-derived signals can influence market outcomes while addressing fairness concerns [22]. The feedback could indicate constrained locations, restricted export levels, preferred flexibility activation, or a need to shift EV charging away from a congested interval. This feedback would allow the market layer to revise candidate matches without requiring the DSO to directly negotiate with every participant.

### Operating envelopes and dynamic constraints

Operating envelopes would define the acceptable range of injections, withdrawals, or flexibility actions at specific network locations. Transactive energy frameworks that combine home energy management, distributed optimal power flow, and P2P trading motivate the use of grid-aware boundaries for local transactions [23]. Reconfigurable distribution-network research also suggests that network topology and operating conditions can change the feasible space for transactive exchanges [24]. In the proposed architecture, operating envelopes would serve as practical communication objects between the DSO and market rather than as formulas presented to participants.

### Coordination with the DSO

The DSO would coordinate with the market platform by providing network status information, validating candidate schedules, and issuing technical feedback when congestion risks emerge. Coupled electricity and carbon trading research indicates that future P2P markets may need to coordinate multiple objectives while remaining embedded in

distribution-network operation [25]. Swarm-intelligent Stackelberg P2P trading also highlights the importance of layered interaction between participant decisions and system-level coordination [26]. **Table 3** summarizes the lower-level network functions, the inputs they require, the outputs they provide, and the congestion feedback mechanisms that would support market revision.

**Table 3.** Lower-level network functions, inputs, outputs, congestion feedback mechanisms, and role in supporting secure market operation in the peer-to-peer energy trading framework

| Lower-level function          | Main inputs from market or grid                                                   | Main outputs to market or DSO                           | Congestion feedback mechanism                                           | Conceptual role in the framework                             |
|-------------------------------|-----------------------------------------------------------------------------------|---------------------------------------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------|
| Network state monitoring      | Candidate trades, EV charging schedule, feeder measurements, topology information | Network status description                              | Identifies areas where the proposed schedule may stress assets          | Provides the situational awareness needed for secure trading |
| Feeder loading review         | Expected injections and withdrawals by location                                   | Loading risk indication                                 | Flags lines or transformers that may approach operational limits        | Protects thermal security during local trading               |
| Voltage condition review      | Solar export locations, demand pattern, flexibility actions                       | Voltage risk indication                                 | Indicates where export reduction or flexible demand adjustment may help | Supports voltage-compatible market outcomes                  |
| Operating envelope generation | Network status, DSO policy, asset limits                                          | Location-specific allowable operating ranges            | Communicates acceptable import or export boundaries to the market       | Converts technical limits into market-usable guidance        |
| Flexibility request formation | Detected congestion, EV availability, controllable load options                   | Request for flexibility activation or schedule revision | Suggests where flexibility could relieve congestion                     | Links network needs to market-based flexibility services     |
| DSO coordination              | Monitoring data, candidate schedules, feedback history                            | Technical approval, warning, or revision request        | Confirms whether the revised schedule is acceptable                     | Maintains accountability for distribution-grid reliability   |
| Feedback logging              | Market revisions, network responses, accepted schedules                           | Audit trail for future validation                       | Records when and why congestion feedback changed market outcomes        | Supports transparency, learning, and regulatory review       |

## EV Flexibility Integration

### Types of EV flexibility services

EV flexibility would be integrated as a set of market-facing services that reshape charging demand while respecting mobility needs. Transactive EV charging research shows that charging can be coordinated through market signals rather than treated as an uncontrollable load [14]. Aggregator reserve-management studies further suggest that EV fleets can

provide structured flexibility services when user constraints and operational commitments are clearly represented [15]. In the proposed framework, these services would include delayed charging, accelerated charging during solar surplus, reduced charging during congestion, and discharge support where vehicle-to-grid participation is technically and contractually enabled.

### Temporal and spatial availability

The value of EV flexibility would depend on both when vehicles are connected and where they are located on the distribution network. Network-aware EV coordination studies emphasize that charge-discharge flexibility must be considered in relation to feeder conditions and local network constraints [17]. Residential flexibility research involving HVACs and EVs also shows that flexible demand resources can interact with distribution-level price and congestion signals [27]. Therefore, the framework would treat EV flexibility as time- and location-sensitive rather than as a uniform resource available everywhere in the system.

### Bidding and dispatch in the market

EV flexibility bids would be submitted by individual EV owners or aggregators to the upper-level market layer as voluntary service offers. These bids would communicate the participant's willingness to shift charging, absorb local solar surplus, reduce demand in constrained areas, or provide controlled discharge where allowed. Frameworks for prosumer participation in P2P trading and flexibility markets indicate that such bids can coexist with energy trades when the market platform distinguishes energy exchange from flexibility provision [10]. The market layer would then include these bids in candidate schedules that are later checked by the lower-level network layer.

### Congestion relief contribution

EV flexibility would contribute to congestion relief by changing the timing and location of charging demand in response to network feedback. Cooperative negawatt P2P trading shows that demand reduction and flexible consumption can be treated as valuable resources in low-voltage distribution networks [28]. In the proposed framework, an EV aggregator could increase charging in a solar-rich unconstrained area or reduce charging on a feeder experiencing stress. This contribution would be coordinated through market instructions and network feedback rather than through direct unmanaged intervention.

### Prosumer incentives and participation

Prosumer participation would depend on transparent incentives, clear service definitions, and confidence that flexibility commitments will not undermine household needs or mobility requirements. Fair-optimal bilevel transactive energy management suggests that fairness is important when community resources are coordinated for collective benefit [29]. The framework would therefore link EV compensation to accepted flexibility services, verified participation, and the role of the service in supporting congestion management. Table 4 summarizes the EV flexibility services, how they would enter the market, and how each service could support network operation.

**Table 4.** EV flexibility services, market participation forms, network value contributions, participant conditions, and roles in congestion management within the peer-to-peer energy trading framework

| EV flexibility service | Market-facing bid description                                                  | Network-facing value                      | Participant condition                             | Role in congestion management                              |
|------------------------|--------------------------------------------------------------------------------|-------------------------------------------|---------------------------------------------------|------------------------------------------------------------|
| Delayed charging       | EV owner or aggregator offers to postpone charging within an acceptable window | Reduces demand during constrained periods | Vehicle must still meet required departure energy | Helps relieve evening or feeder-specific demand congestion |

|                                |                                                                           |                                                           |                                                                         |                                                              |
|--------------------------------|---------------------------------------------------------------------------|-----------------------------------------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------|
| Solar-following charging       | EV offers to charge when local solar surplus is available                 | Absorbs excess local generation                           | Vehicle must be plugged in during solar availability                    | Reduces reverse power flow and solar export stress           |
| Charging reduction             | EV offers temporary reduction from an expected charging level             | Lowers load at a specific node or feeder                  | User accepts reduced charging speed or shifted completion time          | Supports congestion relief during local overload risk        |
| Accelerated charging           | EV accepts earlier or faster charging when the network can accommodate it | Moves demand away from later constrained intervals        | Charger capacity and battery acceptance must permit adjustment          | Prevents future congestion by advancing flexible demand      |
| Aggregated flexibility block   | Aggregator combines many EV bids into one market service                  | Provides a more reliable and visible flexibility resource | Aggregator manages individual user preferences internally               | Allows the network layer to request location-specific relief |
| Vehicle-to-grid support        | EV offers controlled discharge where enabled                              | Supplies local demand or supports voltage conditions      | User contract, charger capability, and battery policy must allow export | Can reduce imports or support constrained local areas        |
| Emergency flexibility response | EV resource accepts exceptional adjustment during network stress          | Provides rapid corrective support                         | Participation rules must define limits and compensation                 | Helps the market respond to unexpected congestion feedback   |

## Framework Integration and Workflow

### End-to-end process overview

The integrated workflow would begin with participant registration, asset characterization, and the submission of solar offers, demand bids, and EV flexibility bids. Bilevel P2P market studies motivate this sequencing because market coordination and network review require different kinds of information [5]. The upper layer would first construct a candidate market outcome, while the lower layer would then evaluate whether that outcome is compatible with distribution-network operation. If the candidate outcome is acceptable, the framework would proceed toward confirmation and settlement preparation.

### Normal operation sequence

During normal operation, the market layer would match local solar surplus with demand and select EV flexibility services that improve market value without triggering network concerns. Studies of P2P trading in microgrids show that local energy exchange can be organized around community-level supply and demand coordination [1]. The network layer would review the candidate schedule and return approval or minor guidance if all relevant operating conditions remain acceptable. The market layer would then confirm accepted trades, communicate participant obligations, and prepare settlement records.

### Congestion handling sequence

When congestion is detected, the workflow would shift from normal confirmation to iterative market-network coordination. Distribution-constrained P2P trading research highlights the need to preserve participant independence while still correcting infeasible trade patterns [8]. The lower layer would communicate the constrained location, affected time interval, and preferred corrective direction in market-usable language. The upper layer would then revise solar matches,

activate EV flexibility bids, or adjust local demand commitments before sending a revised candidate schedule back for review.

## Roles and responsibilities

The market operator would be responsible for participant interaction, trade matching, flexibility procurement, settlement preparation, and communication of revised market outcomes. The DSO would remain responsible for network monitoring, congestion assessment, operating-envelope communication, and technical approval of candidate schedules. Transactive energy system reviews emphasize that home energy management, distributed network operation, and P2P trading must be connected through well-defined coordination roles [23]. In this framework, the DSO guides feasibility without becoming the commercial market maker, while the market operator coordinates trades without overriding grid security.

## Scalability and modularity

The framework would be designed modularly so that additional resources, market products, or network services could be added without redesigning the whole architecture. Multi-market nanogrid research shows that energy trading and ancillary service provision can coexist when mechanisms and implementation interfaces are clearly separated [19]. Shared energy storage studies also indicate that new community assets can be embedded into P2P markets as flexible intermediaries [13]. This modularity would allow the architecture to expand from a small neighborhood pilot to a larger distribution-area platform.

**Figure 1** illustrates the proposed bilevel transactive energy framework in which an upper peer-to-peer market layer coordinates solar offers, demand bids, and EV flexibility services, while a lower distribution-network layer evaluates feeder feasibility, identifies congestion risk, and returns operating-envelope feedback before trades are confirmed.

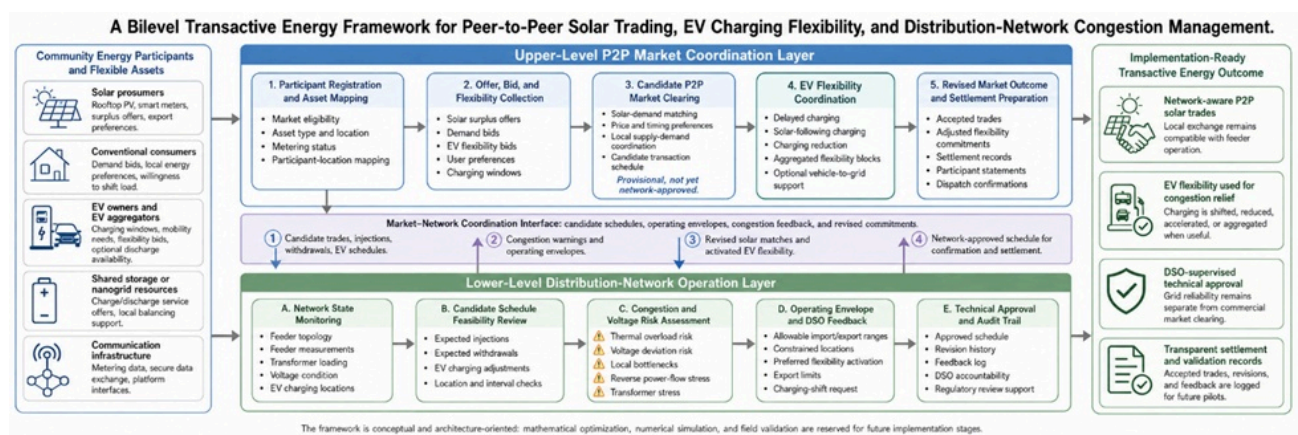


**Figure 1.** Bilevel transactive energy architecture for peer-to-peer solar trading, EV flexibility coordination, and distribution-network congestion management.

## Validation Strategy

### Simulation and test environment

The framework could be validated through staged simulation environments that combine synthetic prosumer behavior, representative feeder models, solar generation profiles, EV charging patterns, and market-platform logic. Prior work on network-aware prosumer scheduling provides a basis for testing how candidate P2P trades interact with distribution constraints [7]. Studies on congestion management with time-sequenced P2P trading also suggest that validation should examine how trades evolve across consecutive operating intervals [11]. The simulation would not need to prove a specific

numerical result at the conceptual stage but would test whether the proposed information flows and feedback loops operate coherently.

## Key performance indicators

Validation indicators would be selected to assess market participation, network security, flexibility usefulness, fairness, and implementation practicality. Fairness-regularized transactive mechanisms suggest that equity and participant treatment should be evaluated alongside technical outcomes [22]. Voltage-regulation P2P studies also motivate indicators related to the ability of prosumers and flexible assets to support local network conditions [21]. These indicators would be interpreted qualitatively in early framework testing and could later be formalized in simulation or pilot evaluation.

## Roadmap for future empirical testing

Future empirical testing could proceed from software-in-the-loop experiments to laboratory demonstrations, regulatory sandboxes, and eventually field pilots with real prosumers and EV charging assets. Renewable microgrid P2P studies connected to distribution grids show that practical validation requires coordination between market design and grid operation [6]. Coupled electricity-carbon trading research also indicates that future pilots may extend beyond energy exchange to include carbon-aware signals and multi-objective coordination [25]. **Table 5** outlines validation stages, test environments, key performance indicators, and expected qualitative outcomes for future work.

**Table 5.** Validation stages, test environments, performance indicators, examined information, and expected qualitative outcomes for the peer-to-peer energy trading framework development and evaluation

| Validation stage                | Test environment                                                   | Key performance indicators                                                              | Information examined                                                | Expected qualitative outcome                                                      |
|---------------------------------|--------------------------------------------------------------------|-----------------------------------------------------------------------------------------|---------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Conceptual consistency review   | Expert review of architecture and workflow                         | Completeness of roles, clarity of interfaces, absence of conflicting responsibilities   | Participant roles, market-network boundary, feedback sequence       | Confirms whether the framework is understandable and internally coherent          |
| Software-in-the-loop simulation | Digital market platform connected to feeder simulation             | Market response to network feedback, flexibility activation logic, communication timing | Candidate schedules, operating envelopes, revised trades            | Demonstrates whether market and network modules can exchange usable signals       |
| Scenario-based stress testing   | Representative feeder with high solar and EV penetration scenarios | Congestion identification, schedule revision effectiveness, participant impact          | Solar export patterns, EV charging locations, constrained intervals | Shows whether the framework can handle challenging operating conditions           |
| Laboratory demonstration        | Controlled microgrid or hardware-in-the-loop environment           | Communication reliability, controller interoperability, data exchange quality           | Metering data, market messages, DSO feedback signals                | Tests whether software and hardware interfaces can support coordinated operation  |
| Regulatory sandbox              | Limited real-world trial with defined market rules                 | Participant acceptance, settlement transparency, DSO confidence, governance feasibility | Enrollment data, accepted bids, feedback logs, settlement records   | Assesses whether the architecture can function under supervised market conditions |

|                       |                                                               |                                                                                 |                                                                    |                                                                          |
|-----------------------|---------------------------------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------------|--------------------------------------------------------------------------|
| Field pilot           | Live distribution area with prosumers, EVs, and DSO oversight | Operational practicality, scalability, stakeholder trust, service repeatability | Real participant behavior, feeder conditions, flexibility delivery | Provides practical evidence for refinement and possible wider deployment |
| Post-pilot refinement | Analysis of pilot records and stakeholder feedback            | Lessons learned, rule adjustments, interface improvements, replicability        | Technical logs, participant feedback, DSO observations             | Converts validation learning into improved framework design              |

## Conclusion

This article has proposed a conceptual bilevel transactive energy framework for coordinating peer-to-peer solar trading, EV charging flexibility, and distribution-network congestion management. The framework separates the market coordination layer from the network operation layer so that commercial exchange and grid security can be addressed through distinct but connected responsibilities. It is designed as an architectural contribution rather than a mathematical model.

The upper-level market layer is responsible for collecting offers, bids, and flexibility services, matching local solar surplus with demand, and preparing settlement-ready market outcomes. The lower-level network layer is responsible for monitoring grid conditions, detecting congestion risks, and communicating operating feedback to the market. Together, these layers create a structured pathway for making P2P trading more compatible with distribution-grid operation.

EV flexibility is positioned as a central bridging resource because it can act as both demand and controllable flexibility. By allowing EV charging adjustments to be bid into the market and reviewed by the network layer, the framework creates a practical mechanism for linking participant incentives with congestion relief. This approach supports a more interactive relationship between prosumer markets, flexible loads, and DSO oversight.

Future work should translate the conceptual architecture into software modules, simulation workflows, pilot-ready market rules, and stakeholder governance arrangements. The framework could also be extended to include shared storage, ancillary services, carbon-aware trading, and more detailed interoperability requirements. Its main value is to provide a clear design language for future research and implementation at the intersection of transactive energy, P2P trading, EV integration, and distribution-network reliability.

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